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Thyristor switches based on hetero and homostructures (Al)GaAs/GaAs for generating high-frequency nanosecond current pulses

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Low-voltage thyristor current switches for generating high-frequency sequences of current pulses have been developed and investigated. The maximum frequency was demonstrated for the GaAs homo-thyristor (HeT) structure, reaching 400 kHz at 35 V. The heterostructure thyristor with an AlGaAs barrier (HoT) exhibited a lower holding current, resulting in a maximum frequency of 170 kHz at 10 V. For maximum voltages of 55 V, the frequencies reached 55 kHz and 40 kHz for the HoT and HeT structures, respectively, generating current pulses with a duration of 3.5 ns and an amplitude of 24 A in the circuit.

Keywords: Thyristor, current switch.

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At present, efficient and compact laser pulse sources operating at high frequencies are needed to create 3D-LIDARs capable of registering fast processes [1]. The work [2] presents lines of 48-element semiconductor lasers with a current source based on GaN-transistors, which made it possible to demonstrate laser pulses with peak power of 600 W due to the realization of pumping by current pulses of duration from 4 to 10 ns with amplitude up to 1 kA at frequencies up to 10 kHz. An alternative approach to pulse pumping is proposed in [3], where a GaAs *S*- diode with an operating voltage of about 200 V was used as a high-current key. As a result, a peak power of 135 W obtained from lasers based on tunnel-coupled heterostructures with efficiencies of about 3 W/A was demonstrated by generating pump current pulses of 1.5 ns duration and 45 A amplitude. In [4], a key based on a high-voltage bipolar avalanche silicon transistor with an operating voltage of up to 110 V was used to generate short pulses, which made it possible to realize the generation of laser pulses with a peak power of 90 W, a duration of 1 ns, and a repetition rate of 200 kHz at the amplitude and duration of pump current pulses of 40 A and 1.14 ns, respectively, and tunnel-coupled heterostructures were also used as emitters. In [5,6], an approach was proposed in which low-voltage optical feedback heterothyristors with operating voltages as low as 30 V were used to realize pulse pumping. This made it possible to create sources providing a peak power of 47 W laser pulses with a duration of 6.4 ns and repetition rates up to 1 MHz at generated pump current pulses with amplitudes up to 60 A. These results allow us to speak about the relevance and practical significance of research aimed at the development of highly efficient high-current switches for pumping high-power semiconductor lasers. In the present work, new results are presented demonstrating the capability of generating high-frequency current pulse sequences by high-efficiency low-voltage thyristor switches.

In [7] it has been shown that the holding current is an important characteristic to ensure the operation of high performance thyristor switches at high frequencies. On the other hand, the processability of thyristor structures is an important condition for their practical use. In this connection, experimental samples of thyristor switches based on two types of structures are considered herein: GaAs homostructure (homothyristor, hereinafter HoT) and AlGaAs/GaAs heterostructures (heterothyristor, hereinafter HeT). All structures were grown by metal-organic chemical vapor deposition (MOCVD) on *n*-GaAs substrates. The HoT structure included the following sequence: layer 1 — *n*-GaAs of thickness 1 μm, layer 2 — *p*-GaAs of thickness 0. 1 μm, layer 3 — p_0-GaAs of thickness 4 μm, layer 4 — *n*-GaAs of thickness 1 μm, layer 5 — *p*-GaAs of thickness 0.5 μm. The HeT structure was characterized by the inclusion of a wide-band barrier layer $Al_{0.1}Ga_{0.9}As$ between layers 1 and 2. Small thicknesses of layers formed on the basis of GaAs provide processability of fabrication of such structures. Blocking was provided by a reverse-biased *p*–*n*- transition with a bulk charge region formed mainly in the p_0-GaAs layer. Despite this, operating blocked voltages reached 55 V for both types of structures. The AlGaAs wide-gap barrier allows controlling the magnitude of the holding current: 60 mA for HoT and 12 mA for HeT.

A simple circuit based on a thyristor chip and a capacitor with a capacitance of 1 nF was used for experimental studies of the possibility of generating a high-frequency pulse sequence. The capacitor was charged from a DC voltage source connected in parallel with the thyristor (a detailed description of the circuit and operation steps is given in [5–7]). For all experiments, the thyristors were switched on by control current pulses with an amplitude of 70 mA and a duration of 200 ns. The frequency of the control pulses set the frequency of the generated current pulses. The approach considered for generating current pulses is the simplest, but the thyristor must be switched to the closed state to effectively charge the capacitor with an external DC voltage source. This is possible when the capacitor is discharged and the current flowing through the thyristor does not exceed the holding current. Fig. 1 shows the dependences of the maximum frequency of current pulse generation in the thyristor–capacitor circuit and the average supply current on the blocking voltage for thyristors based on HoT and HeT structures. In our case, the maximum frequency was determined by the condition that the thyristor can move to the closed state after the capacitor is discharged. Increasing the frequency above the maximum value caused the thyristor to stop turning off and stay open all the time. It can be seen that the maximum frequency of 400 kHz for a blocking voltage of 35 V is demonstrated by the HoT structure with a large holding current, with a current consumption of 34 mA. Increasing the blocking voltage to 55 V reduces the maximum frequency to 55 kHz and the current consumption to 7.6 mA. This drop in maximum frequency may be due to the contribution of the barrier capacitance bias current. Thyristors based on the HeT structure exhibit a maximum frequency of 170 kHz for a blocking voltage of 10 V. Increasing the blocking voltage to 55 V reduces the maximum frequency to 40 kHz and the current consumption to 3.7 mA. It can be seen that for the maximum blocking voltages, the maximum frequencies for both structures have close values, i.e., the influence of the holding current does not have a significant effect. To evaluate the peak current, a 0.5 Ω load resistor was included in series with the thyristor in the circuit. Figure 2, *a* shows the typical voltage dynamics on the capacitor and the current pulse obtained by measuring the voltage dynamics on the load resistor for a thyristor based on the HeT structure. For both types of structures, the achieved duration of current pulses at maximum voltages was about 3.5 ns at half of the maximum. The dependence of the achieved peak current pulse amplitude on the blocking voltage for a thyristor based on the HeT structure is shown in Fig. 2, *b*. It can be seen that the peak current for a voltage of 55 V reaches 24 A. The obtained maximum peak current value is close for both structures. However, a smaller range of operating voltages is observed for the HoT structure. This is due to the fact that the HoT structure does not exhibit fast turn-on dynamics at low voltages. We also evaluated the current dynamics in the thyristor key circuit within the framework of numerical calculation of the transient capacitor discharge in R–L–C-loop with the following characteristics: $R = 1.1\,\Omega$, $L = 2.2$ nH, $C = 1$ nF (Fig. 2, *a*). The obtained results clearly demonstrate the contribution

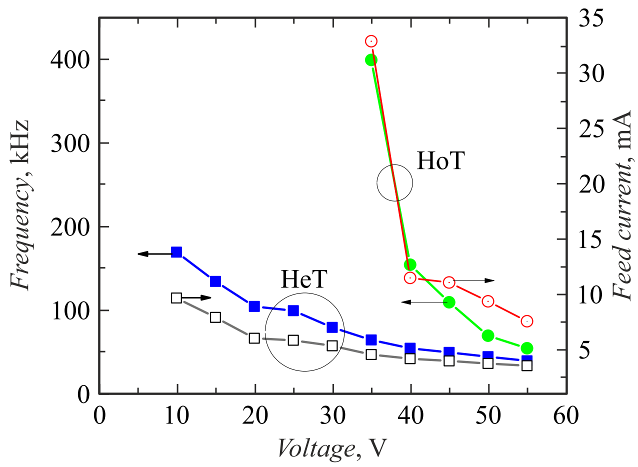

Figure 1. Dependences of the maximum frequency of generation of current pulses in the thyristor–capacitor circuit, as well as the average supply current on the blocking voltage for thyristors based on HoT and HeT structures. The capacitance of the capacitor is 1 nF.

of inductance, with the calculations confirming the given experimental estimate of peak current, pulse shape and duration in the investigated circuit. The modelling showed that a satisfactory match is observed at an equivalent loop resistance of 1.1 Ω, which is higher than the value of the load resistor and may be due to the additional contribution of both the intrinsic resistance of the thyristor key and the capacitor resistance. It should be noted here that the diameter of the anode contact was a value of 170 μm and can be increased to reduce the resistance.

Typical dynamics of the voltage on the capacitor during generation of a high-frequency pulse sequence is shown on the example of thyristors of the HeT structure (Fig. 3, *a*). It can be seen that the voltage dynamics after capacitor discharge includes two sections. The first corresponds to the minimum for the entire cycle and constant capacitor voltage, which forms the „shelf" on the dynamics track. In our case, this value determines the minimum voltage of the thyristor, which is about 1.3 V. The second section corresponds to the capacitor charging process when the thyristor is closed. The lack of voltage rise for the first section may be due to the fact that, despite the low current, the thyristor is in a low resistance open state. This provides a current leakage channel and no capacitor charge, while the thyristor's high resistance closed state transition in the second section ensures that the capacitor is effectively charged.

Figure 3, *b* shows how the duration of the first section varies with the average current of the power supply. It can be seen that the duration of the first section has a threshold minimum value, which is achieved when the average current of the power supply is reduced and for a blocking voltage of 20 V is 960 ns. At the same time, an increase in the average current leads to an increase in the duration of the first section. Studies have shown that the minimum length of

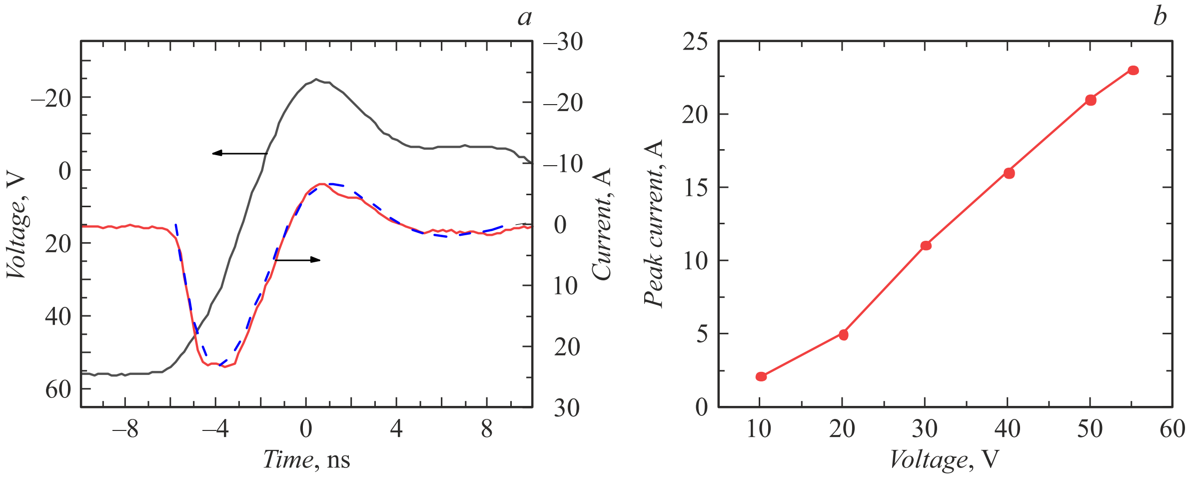

Figure 2. *a* — The time dependence of the voltage across the capacitor at the thyristor on-state transition, as well as the shape of the current pulse measured at the load resistor (solid line) and calculated for $R-L-C$-loop (dashed line) with the following characteristics: $C = 1\,\mathrm{nF}$ to load $R = 1.1\,\Omega$, $L = 2.2\,\mathrm{nH}$ at an initial voltage of 55 V. *b* — the voltage dependence of peak current. Load resistor rating $0.5\,\Omega$, thyristor based on HeT structure, capacitor capacitance 1 nF.

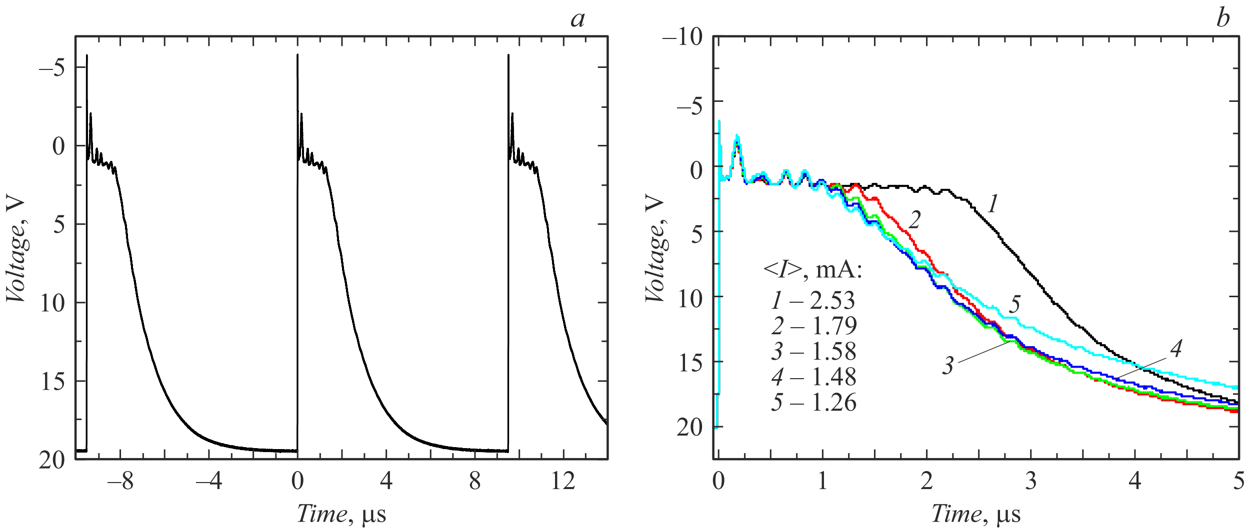

Figure 3. *a* — The time dependence of capacitor voltage in the maximum repetition rate mode. *b* — time dependence of the capacitor voltage for different average power supply currents $\langle I \rangle$. Blocking voltage is 20 V, thyristor key based on HeT structure, capacitor capacitance is 1 nF.

the „shelf" increases as the blocking stress increases. Thus, the maximum modulation frequency of low-voltage thyristor keys in the region of low operating voltages is determined by the magnitude of the holding current, as well as the time of holding the on state after capacitor discharge; for operating voltages close to the maximum value, a significant contribution is made by the bias currents when charging the barrier capacitance of the reverse-biased $p-n$-transition. In this case, the contribution of bias currents to the turn-on process increases as the blocking voltage increases. This is due to the reduction of the p_0-GaAs quasi-neutral base region by expanding the bulk charge region and increasing the concentration of excess holes.

The results demonstrate that the developed low-voltage thyristor keys can be used to solve the pumping problem of high-power semiconductor lasers. The demonstrated peak currents and high generation frequencies indicate the high practical potential of the proposed approach, which can be enhanced by the use of multielement lines and lattices based on low-voltage thyristor switches, which, as shown in [5,6], can raise the peak current without degrading other characteristics.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] R.H. Hadfield, J. Leach, F. Fleming, D.J. Paul, C.H. Tan, J.S. Ng, R.K. Henderson, G.S. Buller, Optica, **10** (9), 1124 (2023). DOI: 10.1364/OPTICA.488853

[2] A. Klehr, A. Liero, H. Christopher, H. Wenzel, A. Maaßdorf, P Della Casa, J. Fricke, A. Ginolas, A. Knigge, Semicond. Sci. Technol., **35** (6), 065016 (2020). DOI: 10.1088/1361-6641/ab8397

[3] I.A. Prudaev, S.N. Vainshtein, M.G. Verkholetov, V.L. Oleinik, V.V.Kopyev, IEEE Trans. Electron Dev., **68** (1), 57 (2021). DOI: 10.1109/TED.2020.3039213

[4] S. Vainshtein, G. Duan, T. Rahkonen, Z. Taylor, V. Zemlyakov, V. Egorkin, T. Skotnicki, W. Knap, Results Phys., **19**, 103509 (2020). DOI: 10.1016/j.rinp.2020.103509

[5] S.O. Slipchenko, A.A. Podoskin, V.S. Golovin, M.G. Rastegaeva, N.V. Voronkova, N.A. Pikhtin, T.A. Bagaev, M.A. Ladugin, A.A. Padalitsa, A.A. Marmalyuk, V.A. Simakov, IEEE Photon. Technol. Lett., **33** (1), 11 (2020). DOI: 10.1109/LPT.2020.3040026

[6] S.O. Slipchenko, A.A. Podoskin, V.V. Zolotarev, L.S. Vavilova, A.Yu. Leshko, M.G. Rastegaeva, I.V. Miroshnikov, I.S. Shashkin, N.A. Pikhtin, T.A. Bagaev, M.A. Ladugin, A.A. Padalitsa, A.A. Marmalyuk, V.A. Simakov, Bull. Lebedev Phys. Inst., **50** (Suppl 5), S527 (2023). DOI: 10.3103/S1068335623170141

[7] S.O. Slipchenko, A.A. Podoskin, O.S. Soboleva, D.A. Veselov, V.V. Zolotarev, N.A. Pikhtin, T.A. Bagaev, M.A. Ladugin, A.A. Marmalyuk, V.A. Simakov, I.S. Tarasov, IEEE Trans. Electron Dev., **63** (8), 3154 (2016). DOI: 10.1109/TED.2016.2582700

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